Characterization of Light Emission From Electron-Beam-Generated Plasmas in Oxygen

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***Abstract*—In this paper, characterization of light emission from pulsed electron-beam plasmas in oxygen is presented. High-speed CCD images reveal light intensity evolution during a pulse. From the individual frames, averaged light intensities were calculated and compared with current measurements. As expected, the comparison suggests that excited species are produced mainly during the pulse. Optical emission spectrum indicates the type of excited species being produced.**

***Index Terms*—Image analysis, plasma diagnostics, plasma sources, spectroscopy, spontaneous emission.**

ELECTRON-BEAM-PRODUCED plasmas have unique plasma characteristics (low electron temperatures, low plasma potentials, and high plasma densities) [1]. While the relative fluxes and energies of ions produced in these plasmas have been extensively characterized [2], the production of excited species and photons and their influence on material processing have not yet been elucidated. In this paper, we show an example of light emission measured using high-speed imaging and optical emission spectroscopy of electron-beam-generated plasmas generated in oxygen.

When a 2-kV energy beam is introduced into a background gas, it ionizes and excites the gas-phase species. These excited species (neutrals or ions) emit light when they relax to lower electronic states, which may be the ground state. The time-resolved images [Fig. 1(a)] show the face of sheetlike beam-generated plasma propagating in front of the processing stage. The electron-beam-generated plasma was produced in oxygen at pressure $p = 50$ mtorr, magnetic field $B = 150$ G, period $P = 10$ ms, and pulsewidth $PW = 4$ ms. The images provide information not only about excitation processes but also about beam uniformity. It should be noted that one is not looking at the beam edge but rather at the face of the beam which is larger than the field of view. The images were obtained using a Phantom v7.3 camera (Vision Research Inc., Wayne, NJ) at 8000 frames per second (125-μs period) and 123-μs exposure per image. The camera was equipped with a 50-mm lens ($f2.8$ f-number and 0.6-m focal length). Typically, the plasma was allowed to run for a few minutes. Then, a video was acquired continuously for 2 s, which was converted to tiff files, and a MATLAB program was used to compute the average image intensities.

Fig. 1(b) shows the normalized electron-beam current densities and normalized averaged light intensities calculated from the images. The comparison was made by assuming that the maximum emission was detected at the maximum current. In general, the detected emission follows the current trace. Further analysis of the electron-beam-generated plasma was conducted using optical emission spectroscopy, where the emitted light is spectrally dispersed and detected. The emission spectrum was obtained using a wideband low-resolution spectrometer (Ocean Optics, HR 2000). The wavelength range was from 200 to 1100 nm. Spectra were taken with an integration time of 1 s, the recorded data were averaged over 20 spectra, and the only correction was for electrical dark signal. Analysis of the emission spectrum requires identification of the routes to excitation. Fig. 1(c) shows the band emission of excited molecular ion O_2^+ from the first negative system ($b^4\Sigma_g - a^4\Pi_u$). Its production is due to a direct excitation and ionization reaction

$$e + O_2 \rightarrow \left(O_2^+\right)^* + e.$$

However, the strongest emission came from excited neutral oxygen atoms $3s^5S^0 - 3p^5P$ ($\lambda = 777.19$ nm) and $3s^3S^0 - 3p^3P$ ($\lambda = 844.67$ nm) produced most likely by the dissociative excitation [3]

$$e + O_2 \rightarrow O^* + O.$$

A weak emission of singly charged excited oxygen ions, produced by dissociative ionization reactions

$$e + O_2 \rightarrow (O^+)^* + O$$

was also detected. For singly charged excited oxygen ions, two transitions are shown $3p^4D^0 - 3d^4F$ ($\lambda = 407.6$ nm) and $3s^4P - 3p^4D$ ($\lambda = 464.18$ nm).

In conclusion, a time-resolved analysis of light emission combined with optical emission spectroscopy has provided useful information about the generation and identification of excited species produced in electron-beam-generated plasmas.

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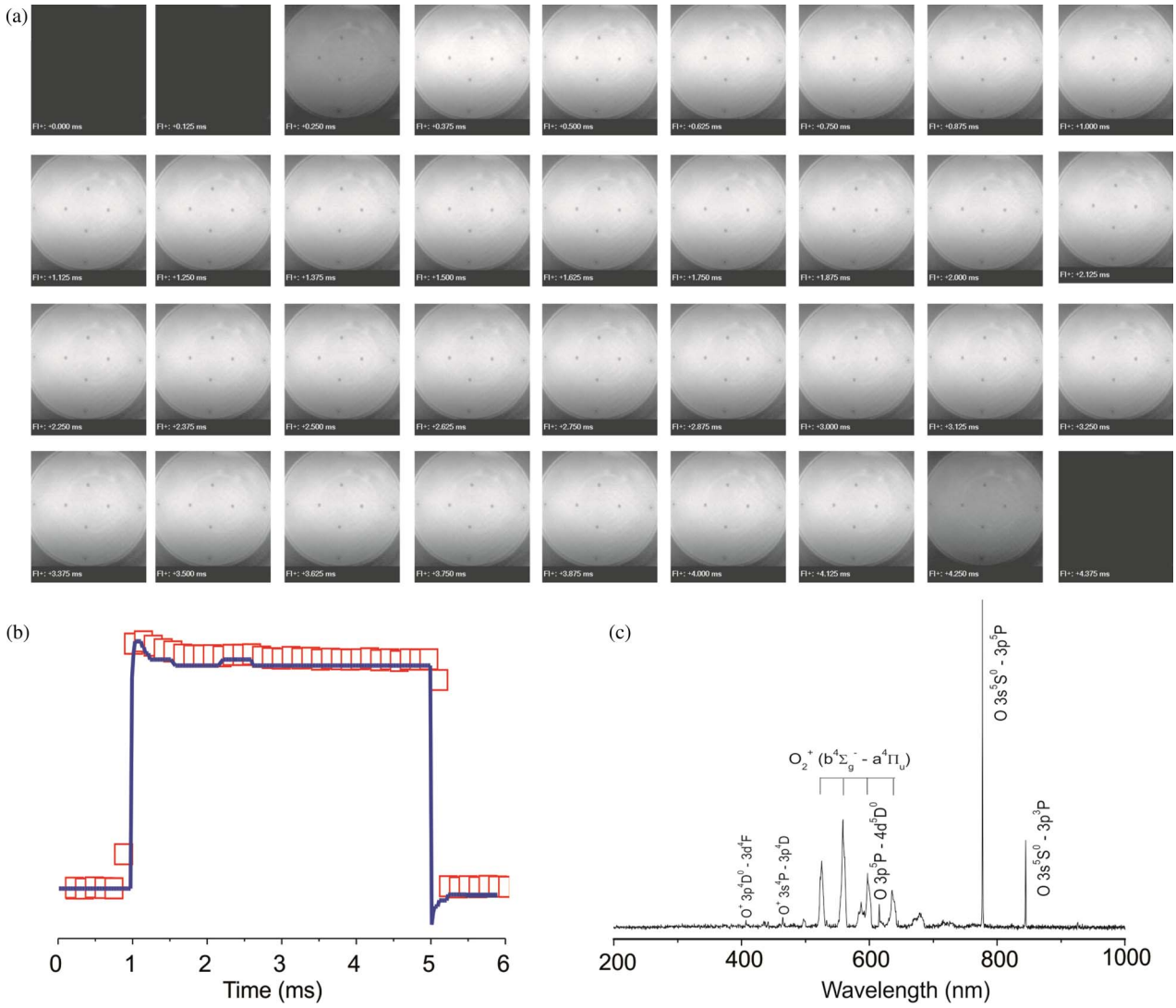

Fig. 1. Light emission from electron-beam-generated plasmas produced in oxygen. (a) Time-resolved images. (b) (Line) Normalized beam current densities and (open symbols) averaged image intensities. (c) Normalized optical emission spectrum.

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